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THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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VI

THE INFLUENCE OF THE LIGHT VOLATILE COMPOUNDS (H_2O, CO_2, ETC.)

The physico-chemistry of the light volatile compounds in the magmas has lately been explained in two treatises published at the same time and independently of each other, namely:

P. Niggli. Die leichtflüchtigen Bestandteile im Magma. Preisschrift von der Fürstlich Jablonowkischen Gesellschaft zu Leipzig, 1920.

Th. Vogt. Lecture in the Society of Science, Kristiania Meeting, April 16, 1920.

Referring to these two treatises and to H. E. Boeke's "Grundlagen der physikalisch-chemischen Petrographie" (1915, especially pp. 256–63), we will begin with a general orientation.

We will discuss a binary system at constant pressure, in which we think of a very high pressure, between A and B, with melting point, respectively critical temperature, S_A, K_A and S_B, K_B where S_B lies notably higher than K_A (illustrated by Fig. 52). The "critical curve" cuts the curve of the gas phase. In this system, when applied to the combination H_2O:silicate, the water at a low temperature will only keep dissolved a trifle of silicate. The eutectic point (E in Fig. 52) of the water solution will consequently practically coincide with S_A which is illustrated by the schematic Fig. 53, copied from Th. Vogt's treatise where, under the signature B, we keep together the different silicate components, for instance, in a granite.

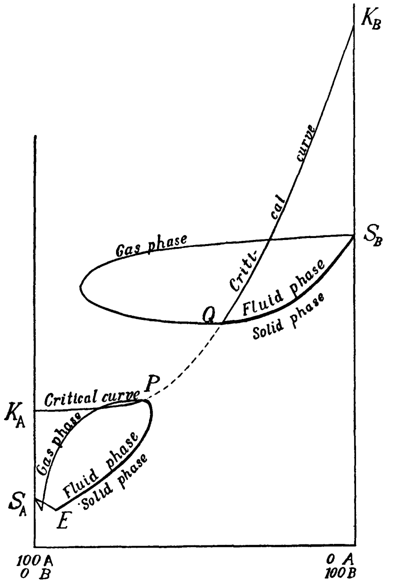

Fig. 52.—The quantitative proportion between A and B as abscisse and the temperature as ordinate.

We may here distinguish between three temperature stages:

1. From S_B (the melting point of the silicate) to Q.

We here get a crystallization of the silicate by continuously decreasing temperature, the quantity of H_2O increasing in the mother liquid (the rest-magma). There is at last produced a magma relatively strongly enriched in H_2O, of the composition Q.

At the same time some of the light volatile compounds escape, so we get a gas phase which can effect pneumatolytic formations. Concerning this we refer to the explanation on the fundamentals given by Th. Vogt and Niggli in Beyschlag-Krusch-J. H. L. Vogt, *Erzlagerstätten*, II, second edition (1921), pp. 555–61.

The gas pressure (the pressure of the escaping gas phase) at S_B (thus for pure B) is very little and increases with the quantity of the light volatile compounds dissolved in the magmatic solution (up to Q). The gases escape when the gas pressure exceeds the external pressure. At a relatively low external pressure, as for the crystallization of a magma at a little depth, the light volatile compounds will consequently escape at higher temperatures, thus also at a relatively earlier stage than at higher pressure, by the solidification of the magma in a depth, for instance, of 5 or 10 kilometers. And in the last case the escaping gas must dissolve in itself more of the silicate compounds. Th. Vogt applies this to very instructive geological examples.

2. At the temperature interval Q–P there exists a gas (H_2O in supercritical condition with some dissolved silicate in gas-formed condition) from which more or less silicate may crystallize directly from the gas.

3. From P (the critical point of H_2O containing some B in solution, which point lies somewhat higher than the critical point, $K_A = 374°$, of pure H_2O) to E (Fig. 52) or S_A (in Fig. 53, where E and S_A practically fall together) we get a liquid very rich in H_2O, which may effect divers hydrotermal formations. Further on we get a gas phase consisting of quite predominant H_2O and only a very little B.

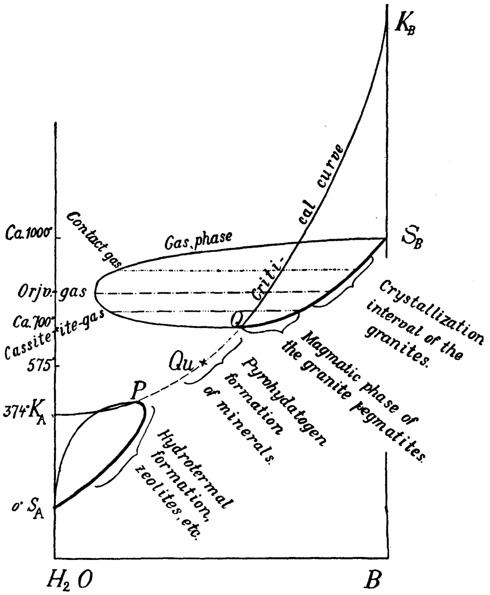
K_B
Criti- cal curve
Ca. 1000°
Contact gas
Gas phase
S_B
Orjv. gas
Ca. 700°
Cassiterite-gas
Q
575°
Qu
P
374° K_A
0° S_A
Crystallization interval of the granites.
Magmatic phase of the granite pegmatites.
Pyrohydatogen formation of minerals.
Hydrotermal formation, zeolites, etc.
H_2O
B

FIG. 53.—System A:B, where A = H_2O and B = silicate (silicates of the granite). Qu = quartz point (inversion points between α and β quartz, at one atmosphere at 575° and at pressure somewhat higher). The pressure may be indicated by axes perpendicular to the plane of the paper. At relatively low pressure in the deep-seated magmas and consequently at high temperature, contact gas escapes, giving as a result the contact metamorphic ore deposits of the Kristiania type. At higher pressure and consequently at a somewhat lower temperature, contact gases escape with a higher solution of silicates, etc., giving, as a result, contact metamorphism of the Orijårvi type ("Orjv. gas"). After Th. Vogt.

By far-advanced crystallization of the granite magma escape "cassiterite gases" (SnF_4, etc.), giving as a result the minerals of the cassiterite deposits.

We shall in the following pages only treat the *crystallization* in a magma, containing light volatile compounds, and not employ ourselves with the pneumatolytic, pyrohydatogen, and hydrotermal processes effected by the escaping gas.

During the crystallization of the magma the light volatile compounds will conduct themselves in different ways:

1. Some will, if the gas pressure is sufficiently high, escape from the magma.

2. Some will be inclosed in the crystallizing minerals as gas- or liquid-inclusions (for instance, the well-known pores in quartz, at low temperature chiefly consisting of liquid CO_2).

3. Some may enter in solid solution into the crystallizing minerals. The quantity calculated by weight—or molecular weight—of these "occluded" gases is, however, very little.[1]

4. Some may, under certain circumstances, enter into the crystallizing minerals, for instance H_2O in muscovite, biotite or hornblende, CO_2 in calcspar, etc.

5. The rest of the gas will remain in dissolved condition in the magma and be concentrated in the mother-liquid, by continuously decreasing temperature until it reaches Q.

These light volatile compounds dissolved in the magma exist in the reciprocal solution in the same manner as the other solution-components. If we think of a magma containing mix-crystal components, as Ab and An besides dissolved water, the water will not influence the mix-crystal system. And if we have a ternary system of two components independent of each other, *a* and *b* and also a little water (in lesser amount than that equivalent to Q on Figs. 52–53), the sequence of the crystallization will be between *a* and *b*, dependent on the quantitative relation between *a* and *b* in relation to a eutectic boundary curve, beginning at the binary eutectic E_{a-b}. The further extension of the curve will be stipulated by the third component, H_2O, present in small amount. With a slight quantity of H_2O the relation between *a* and *b* on the boundary curve will be almost exactly the same as in the binary eutectic E_{a-b}. That is to say, the sequence of the crystallization between

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[1] By heating to below the melting point of the rocks these occluded gases may escape and thereby break the rock into pieces. In this manner many rocks (granite, syenite, gabbro, etc.) may be completely desintegrated by fire.

a and *b* will be displaced only very inconsiderably by the presence of some dissolved water.[1]

We have here supposed that H_2O enters as an independent component (H_2O). But it may also be thought that H_2O, CO_2, HCl, etc., under certain conditions, partly also may form special combinations (for instance H_2SiO_3, H_4SiO_4, H Al SiO_4, etc.), which may be broken up during the run of the crystallization. Hereby there is a possibility for complications which will be very difficult to explore.

In a binary system (under high pressure) of a light volatile component, as, for instance, H_2O, and a silicate, as Ab, An, Or, Ca Mg Si_2O_4, etc., even a little H_2O will effect a relatively considerable depression of the melting point of the silicate, and this depression is nearly proportional to the quantity of H_2O, etc. We refer to the explanation given by Niggli (1920), pages 34–35, and illustrated by his Figure 2, II and III. And in general, the light volatile components (H_2O, CO_2, HCl, etc.) will effect a tolerably considerable depression of the crystallization interval.

From theoretical reasons it must be presupposed that the light volatile components may effect a very considerable increase of the *thin-fluidity*. This is, as far as I know, not verified by laboratory experiments, but that it is the case, may *inter alia* be proved by the fact that the magma of granite-pegmatite dikes, in spite of the low crystallization interval (about 800°–700°) must have been extremely thin-fluid.

With regard to the quantity of the light volatile components in the various eruptive magmas, we may present the following general consideration.

By crystallization-differentiation in a parent-magma with a certain percentage of light volatile components (as, for instance, H_2O), the first separated crystals will, in most cases because of their increased density, sink into a deeper-lying and higher-heated magma-layer where they are dissolved (or resorbed). As we shall see in a later paper, there results from this process, as a rule, after repeated crystallization-differentiations, the *anchi-monomineral magmas* (for example, anorthosite, dunite), where the original quantity of the light volatile compounds in the parent-magma must be considerably diluted.

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[1] In this connection we will cite a portion of the conclusion in the treatise of P. Niggli, "Die Gase im Magma" (*Centralbl. f. Min.*, etc. [1912], pp. 337–38). "Es ergiebt sich aus den (physikalisch-chemischen) Versuchen dass in vielen Fällen (hoher Druck) die Gasmineralisatoren wie eine andere Komponente behandelt werden können, dass also Vogt's Ansicht, dass einfache Schmelzflüsse schon viele petrographische Probleme erleuchtern, richtig ist."

By the segregation of the anchi-monomineral magmas, the light volatile components, so far as they do not escape, will remain in the rest-magma. Extensive crystallization-differentiation results in *anchi-eutectic magmas* (most gabbros, norites, syenites, granites) and as the *final* product of the differentiation running in the anchi-eutectic direction are brought out the *granitic* magmas.

Consequently, we must a priori presume that the light volatile components on an average will be in the smallest quantity in the anchi-monomineral magmas which must have been "dry" or "almost dry melts." A somewhat higher percentage may generally occur in the anchi-eutectic magmas and indeed especially in the granitic magmas. And in the last ones result, as the final solution at a very great depth (after Th. Vogt) where the light volatile components cannot, or can only in part, escape the granite pegmatitic magmas where we may expect a relatively extensive concentration of the volatile components.

As support to this theoretical deduction we shall first point out that *miarolitic druses*, according to my own field observations, generally are completely lacking in anorthosites, dunites and petrographically related rocks. On the other hand, they are very common in many granites, quartz-syenites, etc., and in the miarolitic druses we often find, as well known, a supply of pneumatolytic minerals proving that these druses must have been genetically connected with the volatile components.

Further, according to my own field observations, tourmaline and other pneumatolytic minerals are completely or almost completely wanting in the Norwegian massives of anorthosite and also in the numerous but certainly, as a rule, very small massives of peridotite. By far the most *magmatic-epigenetic* (pneumatolytic, pyrohydatogen, and hydrotermal) ore deposits are connected with acid or intermediate igneous rocks (granite, quartz monzonites, etc.). These ore deposits are, in relation to the extension of the igneous rocks, relatively much rarer with basic igneous rocks, and they are, so far as I know, entirely lacking in the often very large massives of anorthosite. As more fully treated in Beyschlag-Krusch-Vogt (*Die Erzlagerstätten*, Vol. II, 2d ed. [1921], pp. 564–65), this may be explained by the relatively high content of volatile compounds in the granitic magmas. And as far as the granite-pegmatite dikes are concerned, these are, as is known, frequently characterized by a very considerable supply of pneumatolytic (or magmatic-pneumatolytic) minerals.

We further get very instructive information in investigating the relations between *orthorhombic* and *monoclinic pyroxene* on the one hand, and *hornblende, biotite* and *muscovite* on the other, in the various rocks.

As is known, muscovite is noted by Tschermak with the formula $KH_2Al_3(SiO_4)_3$ and biotite (meroxene) with $K_2HAl_3(SiO)_4 \cdot nMg_2SiO_4$, where n is 3 or at times somewhat lower. Some of K usually is replaced by Na, and especially in biotite some of Al by $\dddot{Fe}$ and some Mg by $\ddot{Fe}$. Further some F commonly enters into the mica, replacing O (or HO ?). The relation between K and H moreover, is subject to certain variations. These standard formulas prove that the muscovite contains considerably more H_2O[1] than the biotite. Primary muscovite from granite-pegmatite dikes (and granite) contains, according to the analyses at hand, mostly 5–8 per cent H_2O and 11–9 per cent $K_2O + Na_2O$, and the biotite from granite and other acid igneous rock, mostly 1–2 à 2.5 per cent H_2O and 9–7 per cent $K_2O + Na_2O$.

Also the hornblende commonly carries some H_2O (or HO), viz., in the igneous rocks at most 2 per cent, usually considerably less, and tremolite up to 2.5 per cent.

As to the conditions for the formation of biotite in the igneous rocks, we refer especially to the account given by N. L. Bowen[2] and to the treatise of P. Niggli,[3] "Die gasförmigen Mineralisationen im Magma."

In the previously (pp. 430–35) described orbicular quartz-norite from Romsaas, consisting of *ca.* 63 per cent hypersthene, 8 per cent biotite, 24 per cent plagioclase (on an average $Ab_{42}Or_3An_{55}$), 4 per cent quartz, and a little rutile and apatite, the individualization began with the crystallization of hypersthene in large quantities. Then followed, during a short stage, a simultaneous crystallization of hypersthene and biotite, while the Mg, Fe-silicate present in the magma during the last stage entered totally into the biotite.

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[1] Here and in the following I do not enter upon the question on whether it is hydroxyl, HO, or H_2O, which appears.

[2] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. of Geol.* (1915).

[3] *Geol. Rundschau*, III (1912).

The *anhydrous meta*-silicate *hypersthene* thus during the later stage of the crystallization—even after the percentage of SiO_2 in the residual magma was quite considerably increased, viz., to about 61 per cent—was replaced by the *hydrous ortho*-silicate *biotite.* This must be due to the fact that the original percentage of H_2O of the magma was so small, that at first hypersthene could be formed. But when a considerable quantity of this mineral was segregated H_2O became so strongly concentrated that biotite also could be formed. And during the last stage, when the remaining mass was reduced to *ca.* $\frac{3}{10}$ of the entire rock, the quantity of H_2O was thus very considerably increased, so that the formation of hypersthene ceased, and biotite was formed instead.

As we shall treat more particularly in a later paper, there occur, in the quartz-norite massive at Romsaas, a number of pegmatitic "Schlieren" and dikes of nearly the same mineral composition as the intervening mass between the orbs of the orbicular norites, but with the plagioclase ($Ab_{68}An_{32}$) somewhat richer in Ab and with somewhat more quartz. These pegmatitic "Schlieren," etc., must represent the end-magma, resulting from a very late stage where the quantity of H_2O was still more concentrated. This is in accordance with the pegmatitic structure and moreover with the fact that the Mg, Fe-silicate here only enters into biotite, while hypersthene is entirely lacking.

In several norites from Norwegian localities examined by me, biotite is entirely lacking in almost all thin sections from one single field (Ertelien on Ringerike) while a little biotite occurs in most fields, mostly 2, 3, 4, or 5 per cent, and only as a rare exception, as in the quartz-norite from Romsaas, as much as 8 per cent. Where both hypersthene and biotite occur, the last one always, as just described from Romsaas, belongs to a somewhat later stage than the hypersthene. It is especially to be emphasized that neither the absolute quantity of biotite nor the quantitative proportion between biotite and hypersthene stands in any relation to the composition of the rocks determined by the quantitative chemical analysis. The formation of biotite thus is not dependent on the content of K_2O in the rocks nor on the proportion of K_2O to MgO (or MgO+FeO). In some norites with 0.5–0.7 per cent K_2O the entire quantity of K_2O enters into the feldspar (as $KAlSi_3O_8$ in the plagioclase). In other norites with the same percentage of K_2O, as much as *ca.* $\frac{6}{7}$ of the content of K_2O of the rock may enter into the biotite and only $\frac{1}{7}$ into $KAlSi_3O_8$ of the plagioclase. When we consider this in the light of all the other observations here treated, the conclusion clearly is justified that the cause of the greatly varying quantity of biotite in these rocks must be due to the variations in the quantity of H_2O in the magma. But even in those norites that carry as much as *ca.* $\frac{1}{6}$ of biotite in proportion to the sum of hypersthene and biotite, the H_2O percentage in the magma must have been rather small.

As earlier mentioned, many Norwegian norites and gabbros do not contain any primary hornblende at all, and where this mineral occurs it is somewhat younger than the pyroxene (p. 521). We may here apply the same considerations as those regarding the relation between the hypersthene and biotite in the quartz norite from Romsaas.

The anorthosites constantly carry, as is well known, a small admixture of hypersthene, or sometimes of augite (diallage) and olivine, while primary hornblende seems to be entirely lacking.

As we shall show in a later paper, the peridotite series in the first stage of concentration—carrying about 35–50 per cent olivine and with a chemical composition 41–49 per cent SiO_2, 5–10 Al_2O_3, 6–10 CaO, 0.25–2 alkalies, 10–15 FeO, and 15–25 MgO, thus about 0.75 MgO:0.25 FeO—in almost every case is characterized by some primary hornblende, at times also by some primary biotite. In the progressive concentration of the olivine—and simultaneously with diminishing percentage of Al_2O_3, CaO and alkalies and increasing Mg_2SiO_4 in proportion to Fe_2SiO_4—the hornblende is, on an average, diminishing in quantity and in peridotite rocks with at least 85–90 per cent olivine hornblende as a primary formation is entirely or almost entirely lacking.

The formation of the minerals in both the anorthosites and the olivine rocks—with at least, respectively, *ca.* 90 per cent plagioclase (labradorite-bytownite) and 85–90 per cent olivine (poor in iron)—thus indicates a crystallization of a magma very poor in H_2O.

As to the relation between *hypersthene*, *biotite*, and *biotite+muscovite* in the *alcali granites*, we shall as a beginning cite a very instructive statement by H. Rosenbusch (*Mikroskop. Phys. d. Massigen Gesteine*, II, 1 [1907], p. 71): "Die Analyse eines Hypersthengranites und eines gewöhnlichen normalen Alkaligranite sind nicht sicher zu unterschieden."

In granites with composition

73–77	per cent	SiO_2
11–15	"	Al_2O_3
1.5–3	"	Fe_2O_3+FeO
0.2–0.7	"	MgO
0.25–1.4	"	CaO
5–8	"	$K_2O+Na_2O_4$

(with varying proportion of K_2O and Na_2O) we find, in some cases, though rather rarely, hypersthene—in by far the most cases biotite—and at times biotite+muscovite.

In the hypersthene-granite from Birkrem and environs in the Ekersund Soggendal-field, the hypersthene (opt. neg.), according to my determination, shows axial angle *ca.* 70°, the composition is thus *ca.* 0.64 $MgSiO_4$:0.36 $FeSiO_4$ (equivalent to about 23 per cent MgO and 18 per cent FeO). The quantity of hypersthene in this rock (with *ca.* 73–75 per cent SiO_2) according to microscopical examination is quite small, about 1 per cent, corresponding to *ca.* 0.2–0.25 per cent MgO+0.2 per cent FeO. An analysis published by C. F. Kolderup[1] shows 73.47 per cent SiO_2, 0.12 TiO_2, 15.42 Al_2O_3, 1.02 Fe_2O_3 (including FeO), 0.20 MgO, 1.35 CaO, 5.57 Na_2O and 3.64 K_2O, thus stoechiometric 0.70 Na_2O:0.30 K_2O. The three analyses of charnockite (hypersthene-granite) from Madras[2] (India) with 75.3–77.5 per cent SiO_2, on the other hand show in part a middle proportion of Na_2O to Ka_2O, and in part predominantly K_2O, viz., almost 0.7 K_2O:0.3 Na_2O. We shall group the contents of MgO and K_2O in the just-mentioned analyses of hypersthene-granite with 73.5–77.5 per cent SiO_2:

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[1] Das Labradorfelsgebiet bei Ekersund und Soggendal, *Bergens Museums Aarbog* (1896), p. 96.

[2] Cited from H. S. Washington, *Chemical Analyses of Igneous Rocks*, 1884–1913 (1917, pp. 88 and 956).

per cent MgO....	0.20	0.43	0.69	0.60
" K_2O....	3.64	4.14	3.34	6.13

It appears from this that the formation of hypersthene in these alkali-granites is not dependent on any especially high percentage of MgO (or MgO+FeO) nor on an especially low percentage of K_2O.

According to my examinations of some Norwegian "white granites," relatively rich in acid plagioclase (according to the nomenclature of V. M. Goldschmidt[1] "Trondhjemite") from the north of Norway carrying both *muscovite* and *biotite*, the muscovite occurs exactly in the same way as the biotite. Especially it is to be emphasized that the muscovite-individuals frequently are congested in small aggregates—they thus show "together swimming structure" (synneusis structure) indicating formation at a very early stage—and they are in more places deposited on the small apatite-crystals which serve as "Fixkörper." Some individuals show idiomorphous contours parallel to 001, as well as perpendicular to 001, against the quartz and the feldspar. Most frequently occur the usual lobed outlines, however, as in most of the individuals of biotite in granite.

In some of these muscovite-bearing granites, as, for instance, in a rock from Narvik—with twice as much muscovite, in leaves up to 3 mm. in size, as biotite—we observe crystallographically parallel growths, at times in alternating strata of the two mica-minerals, as described by Rosenbusch (*op. cit.*, p. 57).

In other samples, however, as in a rock from Fustervand near Mosjöen, with nearly twice as much biotite as muscovite—the last one in leaves only *ca.* 1 mm. in size—we observe individuals of muscovite with idiomorphic contours inclosed in the biotite, indicating that the muscovite at least for a great part was formed at an earlier stage than the biotite.

[1] "Geologisch-petrographische Studien im Hochgebirge des Südlichen Norwegens," *Ges. d. Wiss.*, Kristiania (1916).

Rosenbusch (*op. cit.*, p. 51) maintains the view that the formation of muscovite in the granite must be explained as a pneumatolytic process[1] "worauf auch seine weite Verbreitung in den Pegmatiten deutet." This may perhaps to a certain extent be adequate for the muscovite, which belongs to miarolitic druses, but it cannot be applied to the common muscovite evenly distributed in the granite. The structure proves that the muscovite has crystallized from the magma at a very early stage, in part at the same time and in part somewhat earlier than the biotite.

Whether hypersthene, biotite, or biotite and muscovite shall crystallize in acid granites with *ca.* 75 per cent SiO_2 does not depend upon the presence in the magma of those compounds that are shown by the quantitative chemical analysis, nor upon certain variations with regard to pressure, time of cooling, etc. When to this are added the facts that muscovite as a primary formation in igneous rocks is limited to granite-pegmatite dikes and to some granites, and that muscovite is characterized by relatively much H_2O, biotite by a smaller percentage of H_2O, and hypersthene by no H_2O at all, we must conclude that the decisive factor is the varying content in the magma of H_2O (eventually also other volatile compounds).

In the two-mica-granites examined by me, there is up to about twice as much muscovite as biotite. If we turn to the granite-pegmatite dikes, however, we find at times, though very rarely, as in the case of some districts of Smaalenene in Norway, muscovite only, without any biotite at all, and the quantity of muscovite may here rise to as much as about 10 per cent.

The great majority of alkali-granites are characterized by biotite. Two-mica-granites, in Norway as elsewhere in the world, are rare, and hypersthene-granites, so far as yet known, are still more rare.

The content of H_2O in the granite-magma thus in most cases must have been lying within the interval that gives biotite. As a rare exception only, the quantity of H_2O may have been so small, that hypersthene has been formed (or, principally in somewhat more basic granites, a monoclinic pyroxene, besides or instead of hypersthene), and relatively seldom only the content of H_2O, etc., was somewhat higher, so that muscovite was formed together with biotite. In granite-pegmatite dikes of analogous chemical composition the content of H_2O, etc., throughout must have been considerably higher, as we here never find hypersthene or diopside, but mica and not seldom muscovite together with biotite, occasionally even muscovite alone without biotite.

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[1] While H_2O dissolved in the magma appears in the same manner as the other components, I do not find it natural or right to extend the meaning of the term pneumatolysis to include the formations of minerals, as biotite or muscovite where the magmatic dissolved H_2O was co-operant.

And if we further draw a parallel between the granites (with *ca.* 75 per cent SiO_2) on the one hand and norites, gabbros, anorthosites, etc. (with *ca.* 50 per cent SiO_2), on the other, we will find that mica plays a predominant part in the first-mentioned acid rocks, while in the last-mentioned basic rocks biotite is much more subordinate than the pyroxenes, and muscovite is entirely lacking.

By three different methods of investigation, viz., in the study of the distribution of miarolitic druses, in the study of the magmatic-epigenetic formations of ore deposits, etc., connected with igneous rocks, and in the study of the relation between mica (biotite, eventually also muscovite), and in part also hornblende, and pyroxene, we thus get a confirmation of the theoretically drawn conclusion that the granites on an average contain the highest percentage of H_2O, etc.

Then we come to the question of how much H_2O, etc., there may have been present at the start of the crystallization in the magma and especially in the granite-magma.

In the muscovite granite-pegmatite dikes there may occur about 10 per cent muscovite containing 5–8 per cent H_2O. In proportion to the entire magma there thus entered into the *early* crystallizing mica *ca.* 0.5–0.8 per cent H_2O. But still there must have been present so much H_2O that the later separated minerals might also obtain the pegmatitic structure. This quantity of H_2O (with CO_2, etc.) escaped, except those small quantities that entered into the microscopic pores or was occluded in the separating minerals. This, including the content of H_2O in the mica, will only make 1 per cent by weight of the entire magma. The gas that escaped in the course of the crystallization, at least in part, will have formed miarolitic druses. These play a rather subordinate part in regard to the quantity in the granite-pegmatite dikes, however.

Even in the granite-magma the quantity of H_2O will hardly have amounted to much more than a few per cent. And the crystallization of the igneous rocks must, as pointed out by many earlier investigators, among them also myself, be conditioned by the decreasing temperature of the magma and not by the diminution of volume occasioned by the escaping H_2O, etc.

According to Clarke's well-known calculation the earth's crust consists to a depth of 10 miles (=*ca.* 16 km.) at a medium density of the rocks of 2.7, of

93.39 per cent solid crust, with 2.02 per cent H_2O
6.58 " " ocean, with *ca.* 97 per cent H_2O
0.03 " " atmosphere

If we were to presume that the entire quantity of water of the ocean was supplied from the igneous magmas, and assume a medium thickness from the solid crust of three times 10 miles=*ca.* 48 (or 50) km., we would get a quantity of H_2O:

$$\tfrac{1}{3}\times 6.58\times 0.97+97.81\times 2.02=4.06 \text{ per cent } H_2O.$$

This value, *ca.* 4 per cent, must indicate the maximum original content of H_2O in the initial parent-magmas. But of this again a considerable part must have escaped before the parent-magmas could have been cooled so far that crystallization-differentiation began. The various partial magmas, resulting from magmatic differentiation, which, crystallized to form the igneous rocks, must thus, on an average, have contained less, very likely quite considerably less, than 4 per cent H_2O.

In concluding, I wish to note that I have learned much from P. Niggli's great work: "Die leichtflüchtigen Bestandteile im Magma" (1920), but I cannot endorse his statement (pp. 123–38) that the volatile compounds have been the important factor in magmatic differentiation. This will be more closely treated in a later paper.

[*To be continued*]